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A New-Type of Super High Frequency Optical Modulation Scheme

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A possibility of super high speed optical modulation scheme is proposed. An example of this concept is as follows: Light wave is modulated succeedingly through cascaded light modulators by a sub-carrier to produce a modulated light wave at a harmonic frequency which is higher than the feasible frequency of each of the element modulators. This paper presents the basic theory and experimental verification of the above scheme.

1 Introduction

Since the frequency of lightwave is very high, it has a latent possibility of extremely wide-band transmission of signals. However, only a small part of this capability is utilized at the present time, mainly because there has been developed no modulators nor demodulators that can operate at frequency higher than millimeter wave.

Recently, high-speed optical modulators and demodulators that operate at several ten's of gigahertz have been developed[1,2,3]. However, there are limitations that the electro-optical components can not exceed a certain speed. As a way to overcome these limitations and extend the operating frequency range, we previously proposed the high speed optical modulation and demodulation techniques such as cascaded modulation[4], square modulation[5] and frequency conversion demodulation.

In this paper, we will present a basic theory and show some experiments, that is, some methods to modulate a lightwave at frequency higher than the modulation frequency.

2 Basic Theory of Harmonic Modulation

2.1 Two-stage cascaded modulation

Lightwave modulated at frequency ω is expressed by

$$P = P_o\{1 - m - m\cos(\omega t + \theta)\}, \tag{1}$$

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noting that in the usual optical modulators the instantaneous peak power of the modulated lightwave cannot exceed the average input optical power P_o. Since the magnitude of the lightwave should be positive, the modulation depth, m must satisfy $|m| \leq 1/2$ ($m = 1/2$ means 100% modulation). If the modulated lightwave is modulated again in reverse-phase with the same type of modulator, we obtain

$$P = P_o\{1 - 2m + m^2/2 - (m^2/2)\cos 2(\omega t + \theta)\}. \tag{2}$$

This tells us that the lightwave is modulated at twice the fundamental frequency ω with the fundamental frequency ω being cancelled[4]. If we set the modulation index of each modulator to be 100%, that of 2ω frequency component also becomes 100%.

2.2 The n-stage cascaded modulation

The above mentioned modulation technique can be extended to an arbitary number of cascade connected modulators. If we connect the n modulators in cascade, the modulated lightwave is expressed as

$$P = P_o \prod_{k-1}^{n} \{1 - m - m\cos(\omega t - 2k\pi/n)\}, \tag{3}$$

where the phases of each modulator were shifted by the same value to achieve the total phase shift of 360°. Since the n-th root of 1 is $\exp(j2k\pi/n)$, we can write as

$$x^n - 1 = \prod_{k=1}^{n} \{x - \exp(j2k\pi/n)\}. \tag{4}$$

Substituting $x = \exp(\alpha + j\omega t)$ into Eq.(4), and taking the square of its absolute value and dividing it by $2\exp(n\alpha)$, we obtain

$$\cosh(n\alpha) - \cos(n\omega t) = 2^{n-1} \prod_{k=1}^{n} \{\cosh\alpha - \cos(\omega t - 2k\pi/n)\}. \tag{5}$$

If we set

$$\cosh\alpha = (1 - m)/m, \tag{6}$$

we have

$$\exp(\pm\alpha) = \{1 - m \pm (1 - 2m)^{1/2}\}/m. \tag{7}$$

With the aid of these relations above, Eq.(3) is calculated to be

$$P = P_o \cdot A\{1 - M\cos(n\omega t)\}, \tag{8}$$

where

$$\begin{aligned} A &= [\{1 - m + (1 - 2m)^{1/2}\}^n + \{1 - m - (1 - 2m)^{1/2}\}^n]/2^n \\ M &= 2m^n/[\{1 - m + (1 - 2m)^{1/2}\}n + \{1 - m - (1 - 2m)^{1/2}\}] \end{aligned}$$

That is to say, if we connect the n modulators in cascade, n-th orther harmonic modulation is achieved with the fundamental and any other harmonic frequencies being cancelled[4]. If the

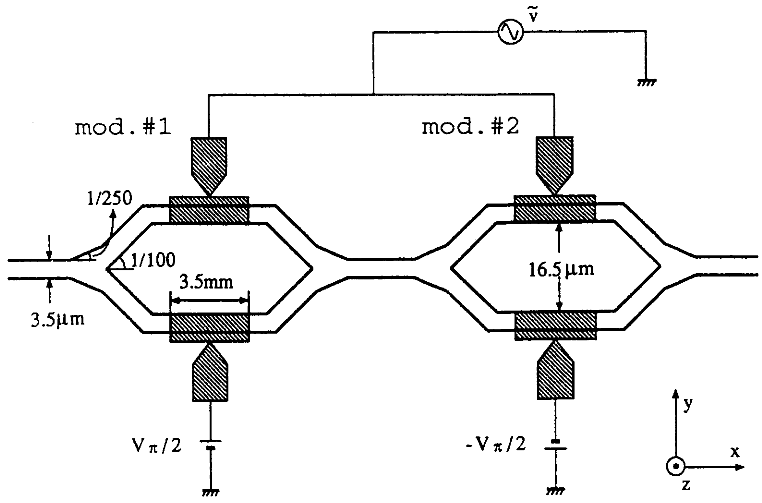


Figure 1: Design structure and parameters of the waveguide

modulation index of each modulator is $100\%(m = 1/2)$, that of n-th order harmonic modulation also becomes 100%. In the case of passive optical modulators, the magnitude of the optical power decreases to $P/2^{2n-1}$. However, if modulation index m of each modulator is small, the modulation index of the n-th order harmonic modulation decreases to about $2(m/2)^2$ without the optical power decreasing. So, the modulation index should be determined according to the type of application.

2.3 Square modulation

If a modulator having a square characteristic is used, modulation at twice the sub-carrier frequency is obtained with a single optical modulator according to the trigonometric formula,

$$P = P_o \cos^2(\omega t + \theta) = P_o\{1 + \cos(2\omega t + 2\theta)\}/2. \tag{9}$$

Needless to say, higher harmonic modulation is also possible by cascading a plural number of this type of optical modulators, following the same principle as described above.

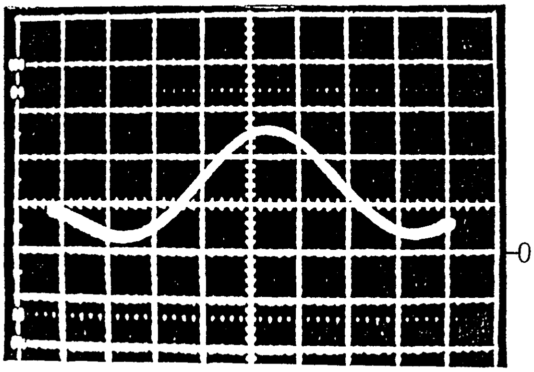
2.4 Light interference modulation

There are a number of research works relevant to optical interference modulators. In the ordinary type of modulator, the injected lightwave is first divided into two by a hybrid coupler (or Y divider) and each wave is phase-modulated in reverse-phase by a modulation signal v and then added with another hybrid coupler (or Y coupler). As the phase shift ϕ is proportional to the modulation voltage, we may write $\phi = \pi v/2V_\pi$. Then we have the AM light output wave given by

$$E/E_o = e^{j\phi}/2 + e^{-j\phi}/2 = \cos(\pi v/2V_\pi). \tag{10}$$

If we apply a sinusoidal modulation signal

$$v = (2V_\pi/\pi)m\sin(\omega t + \theta)$$



horizontal axis : applied voltage 5V/div
vertical axis : output voltage 1mV/div

Figure 2: Observed half-wave voltage

without dc bias, then the second harmonic modulation is obtained

$$E/E_o \simeq J_o(m) + 2J_2(m)\cos(2\omega t + 2\theta), \tag{11}$$

where J stnad for the Bessel Function and the modulation index m is assumed to be small. If the modulation index m is increased so that $J_2(m) = 0$, then fourth harmonic modulation is directly obtained such that

$$E/E_o = J_o(m) + 2J_4(m)\cos(4\omega t + 4\theta). \tag{12}$$

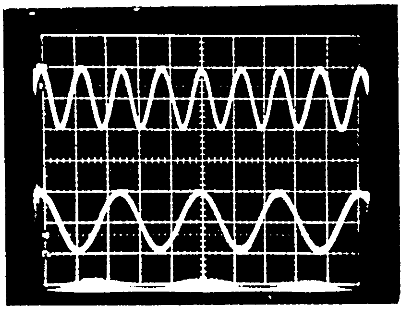
Because the above mentioned harmonic modulation is accompanied by nonlinear characteristics, it is not suited to direct analog modulation. But, this method can be utilized effectively in sub-carrier multiplexed optical communication systems, in which the sub-carrier is modulated with the base-band signal in the mode of modulation of either one of FM, PM, PSK or FSK.

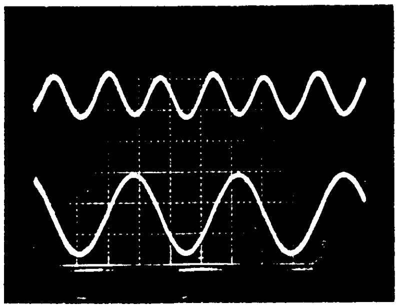
3 Experiments

3.1 Fabrication of the optical modulator

A two stage cascaded interferometric optical modulator was fabricated by Ti diffusion on a z-cut $LiNbO_3$ substrate. The design structure and parameters of the waveguide are shown in Fig. 1. The parameters were chosen for a He-Ne laser ($0.633\mu m$) as a light source.

We first fabricated optical waveguide for a modulator by evaporating Ti 30nm thick onto the z-cut $LiNbO_3$ substrate. The Ti was patterned using photolithography and chemical wet etching, and was diffused into the substrate at 1020°C for 5 hours with O_2 flowing over it which had been passed through pure water in order to reduce surface waveguiding. A 150nm buffer layer of SiO_2 was sputtered onto the substrate before to the electrodes were deposited by evaporating Al by 200nm thick onto the buffer layer and patterning it using photolithography and chemical wet etching. The electrode lengths were set to be 3.5mm, the gap $16.5\mu m$ and





Top : Output(400kHz)　Bottom : Input(200kHz)

(a) Square modulation　　(b) Cascaded modulation

Figure 3: Results of the modulation experiment

the width $15\mu m$. The substrate edges were optically polished to inject lightwave efficiently from a He-Ne laser. Under this condition, we expect that only the dominant mode may be guided. The loss of the Y-branch is expected to be less then 1dB[6]. The half-wave voltage of each modulator of this structure was estimated to be 14V from the half-wave voltage formula[7] with the reduction factor for the applied electric field $\Gamma \simeq 0.3$. This is in good agreement with measurement, as shown in Fig. 2.

To make a high-efficiency and wide-band optical modulator, traveling-wave type electrodes of long length is desirable. However, our major interest of this experiment was to confirm the principle of the above-mentioned modulation theory, so we did not lay much stress on bandwidth and half-wave voltage in fabricating the electrodes of our optical modulator.

3.2 Modulation experiment

We carried out the square modulation experiment first. The bias was chosen in the region of square characteristic curve of Fig. 2, near 0V or 15V. We applied modulation signal at 200kHz and obtained a detected signal at 400kHz as shown in Fig. 3. We performed next an experiment of cascaded modulation. The square of Eq.(10) gives the light wave power modulated :

$$P = \frac{1}{2}P_o\{1 + \cos(\pi\frac{v}{V_\pi})\} \tag{13}$$

If the bias voltages of each modulator are chosen at $v = \pm V_\pi/2$ as shown in Fig. 4, phase difference of π is produced between the two modulators. So, we set the modulation voltages to be $v = \tilde{v} \pm V_\pi/2$ with $\tilde{v} = V\cos(\omega t + \theta)$. Providing that the interferometric optical modulators operate ideally, the light output amplitude may be calculated as

$$P(\tilde{v})/P = \frac{1}{4}\{1 + \cos(\pi\frac{\tilde{v}}{V_\pi} + \frac{\pi}{2})\}$$

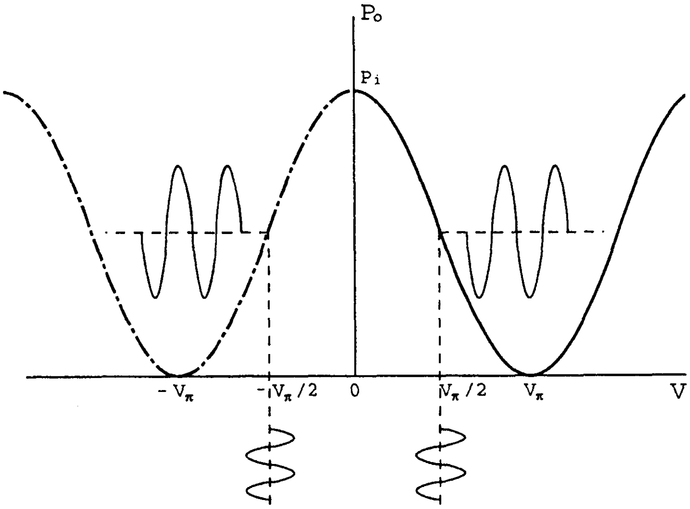


Figure 4: Bias points of the two-stage cascaded modulation

$$\{1 + \cos(\pi\frac{\hat{v}}{V_\pi} - \frac{\pi}{2})\} \quad \simeq \quad \frac{1}{8}[2 - (\pi\frac{V}{V_\pi})^2\{1 + 2(\omega t + \theta)\}] \tag{14}$$

where we have assumed for simplicity that $|V/V_\pi \ll 1$. The modulation frequency has been doubled with the fundamental frequency being cancelled.

In the experiment, we selected the bias of the two modulators to be $V_\pi/2 = 7V$ for mod. ♯1 and $-V_\pi/2 = -7V$ for mod. ♯2, so that we may obtain anti-phase cascaded modulation. Since the modulation characteristics of the two modulators were slightly different from each other, we had to adjust the modulation depths of the two modulators to cancel the fundamental frequency completely. That is, doubled frequency modulation was obtained as shown in Fig. 3(b) similar to the square modulation experiment.

3.3 System experiment

As an example of the application of the present scheme of modulation and demodulation to some optical communication system, a model experiment has been carried out at lower frequencies. A schematic diagram is shown in Fig. 5.

In this model experiment the two stage cascade modulator was also utilized. Only the front end modulator was driven to acquire the square wave characteristic. The rear-end modulator was used to apply a local signal in order to down-convert the doubled sub-carrier signal[8]. The down-converted signal was detected by an APD. The sub-carrier of 100kHz was FM-modulated with a base-band signal of 1kHz. The FM-modulated sub-carrier was fed to the fore-end electrodes so that the lightwave from the He-Ne laser was modulated at twice the sub-carrier frequency. Before the doubled sub-carrier signal was detected with an APD, it was modulated once again at the local signal frequency of 180kHz. The down converted sub-carrier signal of 20kHz is detected directly by an APD along with the dominant signal. The output of the APD was fed to a 20kHz band-pass filter to select the down-converted sub-carrier signal of 20kHz.

Finally, the FM-demodulator was used to demodulate the base-band signal. We obserbed the change in the waveform at each stage from the base-band siganl to the final demodulation

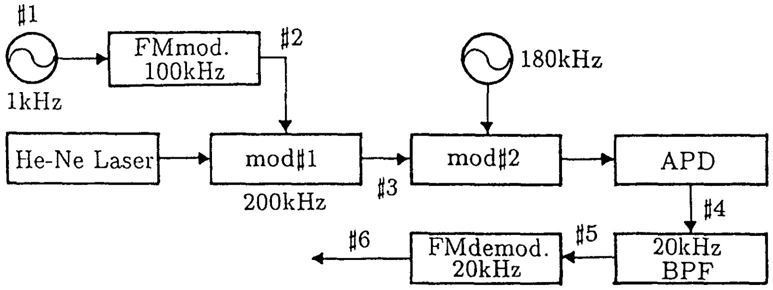


Figure 5: A schematic diagram of model experiment

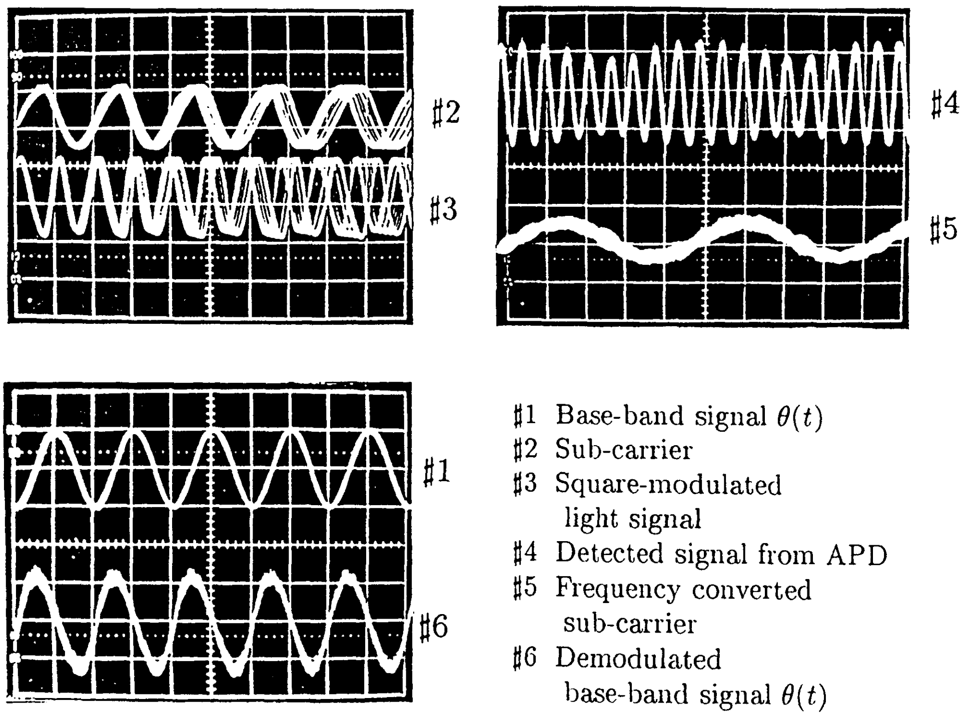


Figure 6: Waveform of each stage(Time scales arbitrary)

signal. The FM-modulated sub-carrier signal of 100kHz and the square modulated sub-carrier signal of 100kHz are shown in Fig. 6(a). As shown in Fig. 6, a doubled sub-carrier signal of 200kHz was observed. Fig. 6(b) shows the waveform after that the 180kHz local signal is applied to the rear-end modulator. Fig. 6(c) shows the finally demodulated signal compared with the orginal signal. The result shows that this kind of optical communication system can transmit signals without distortion.

If we apply this technique, as an example, to the conventional optical communication system above at the frequency presently used, we may be able to exploit the frequency range which is left unused. In order to apply this system to a presently used optical communication system, a kind of filtering must be employed, so that the signal included in the frequency range higher than the cutoff frequency of the pgotodetector should not interfere with the base-band signal lower than cutoff frequency. This sort of filtering or frequency multiplexing will be reported in future.

4 Discussion

High speed lightwave modulation does not necessarily mean high capacity transmission, simply because it is possible to generate an ultrafast CW lightwave, it does not follow that the transmission of high capacity information using the ultrafast CW lightwave is possible. However, if an ultrafast CW lightwave is obtained, there are many attractive applications using this phenomena.

The cascaded or square modulation technique, while utilizing a conventional relatively low-speed optical modulator, can generate an ultrafast CW lightwave. Furthermore, by means of integration of many modulators in a single substrate, input/output loss can be minimized.

We will show how these modulation techniques are used to construct a very high capacity lightwave transmission system. When an optical modulater is used in a very high capacity transmission system, the optical modulator need not cover wide-bandwidth. Even in the case that the optical modulator has narrow-bandwidth, if high speed lightwave modulation is possible, very high capacity information can be transmitted.

For example, when we utilize cascaded modulation, a microwave or millimeter wave was used as the sub-carrier, and the lightwave as the carrier, making it possible for a very high capacity lightwave transmission system to be constructed. Fig. 7(a), as an example, adopted cascaded modulation to increase the transmission capacity. The output from the light source is multiplexed by the $1 \times n$ multiplexer. At channel 1(CH1), Mod.1 is modulated at the sub-carrier ω_m which is modulated by the base-band signal $S_1(t)$. At channel 2(CH2), Mod.1 is modulated at the sub-carrier ω_m which is modulated by the base-band signal $S_2(t)$, and the output of Mod.1 is cascaded modulated again by the sub-carrier ω_m in Mod.2. The signal $S_2(t)$ moves to twice the frequency of $2\omega_m$. The next stage channels are also modulated with the same modulation technique. The output of each channel is demultiplexed by the $n \times 1$ demultiplexer and transmitted through a single optical fiber. The spectrum of lightwave transmitted through the optical fiber is shown in Fig. 7(b). Utilizing the high frequency region of the lightwave which has left unused, we can transmit very high capacity information through a single optical fiber.

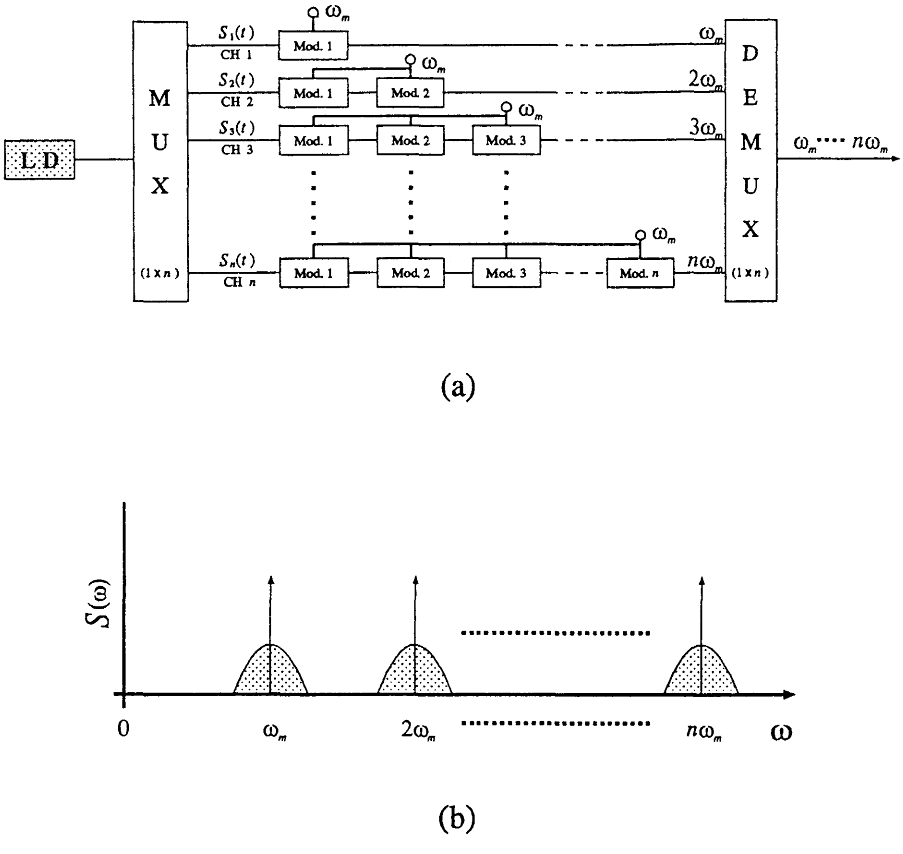


Figure 7: (a) An example of very high capacity optical transmission system adopting the cascaded modulation. (b) Frequency spectrum.

5 Conclusion

A method of high-speed optical modulation techniques have been proposed, and the possibilities of the techniques were tested experimentally at lower frequencies. A two-stage cascaded optical modulator was fabricated to demonstrate the proposed high-speed optical modulation theories. We have succeeded in transmitting the FM-modulated signal using the cascade modulation technique at the lower frequency of 200 kHz. A more realistic and detailed investigation of this scheme at higher frequencies may be future task. Research of sub-carrier multiplexing systems using a new type filtering to increase the existing optical communications is now undertaken.

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